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DOE/NASA/33408-3
NASA TM-102085

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(NASA-TM-102085) COMPARISON OF CONCEPTUAL DESIGNS FOR 25 kWe ADVANCED STIRLING CONVERSION SYSTEMS FOR DISH ELECTRIC APPLICATION Final Report (NASA, Lewis Research Center) 16 p CSCL 10B G3/85 N89-26781 Unclas 0212643

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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
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Prepared for the
24th Intersociety Energy Conversion Engineering Conference
cosponsored by IEEE, AIAA, ANS, ASME, SAE, ACS, and AIChE
Washington, D.C., August 6–11, 1989

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes[1]
Printed copy: A03
Microfiche copy: A01

[1]Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from NTIS at the above address.

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ABSTRACT

The Advanced Stirling Conversion System (ASCS) Project is managed by NASA Lewis Research Center through a cooperative Interagency Agreement with DOE. Conceptual designs for the ASCS's were completed under parallel contracts in 1987 by Mechanical Technology Inc. (MTI) of Latham, NY, and Stirling Technology Company (STC) of Richland, WA. Each design features a free-piston Stirling engine, a liquid metal heat pipe receiver, and a means to provide about 25 kW of electric power to a utility grid while meeting DOE's long term performance and cost goals. An independent assessment showed that both designs are manufacturable and have the potential to easily meet DOE's long term cost goals.

INTRODUCTION

The Department of Energy's (DOE) Solar Thermal Electric Technology Program, Sandia National Laboratories Albuquerque (SNLA) is evaluating heat engines for terrestrial Solar Distributed Heat Receivers. The Stirling engine has been identified by SNLA as one of the most promising engines for terrestrial applications. Recent studies by SERI and EPRI have concluded that dish systems utilizing reflux receivers integrated with Stirling engines are a promising candidate as a future power source for the utilities industry. The free-piston Stirling engine has the potential to meet DOE's long term goals for performance and cost.

The Stirling Technology Branch at NASA Lewis Research Center is responsible for a variety of projects, including both the free-piston and kinematic Stirling engines. The Stirling cycle has been pursued as a candidate dynamic power source for future high-power space conversion systems at NASA Lewis since the 1960's. Current projects for space power requirements are shown in Fig. 1. Space power requirements include high efficiency, very long life, high reliability, and low vibration. In addition, system weight and operating temperatures are important. The free-piston Stirling shown schematically in Fig. 2, has the potential for a highly reliable engine with long life because it has only a few moving parts, noncontacting gas bearings, and can be hermetically sealed. A discussion of free-piston Stirling technology for the space power application is contained in Ref. 1. Although both applications, terrestrial and space power, appear to be quite different, their requirements complement each other.

The development of alternative powerplants for the Department of Energy (DOE) in the late 1970's initiated the DOE's Automotive Heat Engine Program, which included the development of both the gas turbine and Stirling engine for automobiles. These programs were planned and implemented by NASA Lewis. As a result of these programs, a unique technology base and Stirling expertise was gradually developed at NASA Lewis during the 1970's. In 1981, the applicability of both the gas turbine and Stirling automotive heat engines for solar thermal power applications, was evaluated.[2] Although, both the gas turbine and Stirling have the potential to meet the high efficiency goals for the solar program, it was determined that a number of modifications were needed to adapt these automotive engines for the solar application. The duty cycles for these applications are quite different, the automotive application requiring frequent speed and power changes, while the solar application has a constant speed and power requirement. Areas primarily of concern with these engines were the life and reliability requirements, along with issues of initial and life cycle costs for the solar application. In summary, this report concluded, that it was more desirable to start with a clean sheet, and design an engine specifically for the solar thermal application, rather than adapt one of the automotive heat engines.

A comparison of the kinematic and free-piston Stirling engines for the solar application is shown in Table I. The kinematic engine was originally designed for the automotive duty cycle, while the free-piston Stirling engine is being developed for the long life space power application. Major differences shown are in the drive and gas systems. The drive system components (drive shaft, bearings, oil pump, piston rings, crossheads and shaft seals, etc.) and the gas system (the power control system) components (compressor, check valves, storage tank and power control valve, etc.) have wear potential which would reduce engine life in the kinematic configuration. Design life of between 10 000 and 20 000 hr should be easily obtained for reciprocating engines such as the kinematic Stirling, when modified for operation with a constant speed and load. The free-piston Stirling engine, however, has no significant side loads, which minimizes wear mechanisms and allows for long life. The use of noncontacting gas bearings during operation should permit the free-piston to exceed the 60 000 hr life requirement for the solar application without difficulty. In addition, the free-piston Stirling can

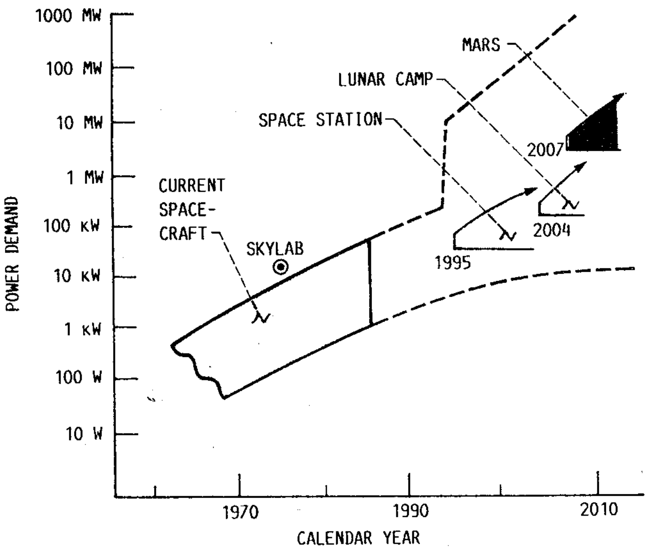

FIGURE 1. - FUTURE SPACE POWER REQUIREMENTS.

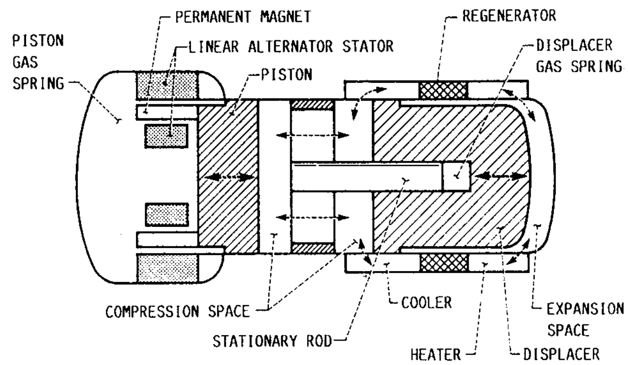

FIGURE 2. - FREE-PISTON STIRLING ENGINE WITH LINEAR ALTERNATOR.

TABLE I. - COMPARISON OF KINEMATIC AND FREE-PISTON STIRLING ENGINES COMPONENTS FOR SOLAR APPLICATIONS

	Kinematic (automotive)	Free-piston
Heat source	Solar	Solar
Receiver	Liquid metal heat transport system	Liquid metal heat transport system
Drive system	Shaft(s) Bearings Piston rings Crossheads Shaft seals	Gas bearings Gas springs
Lubrication system	Oil pump	Gas bearings
Working fluid (pressure)	He (15 MPa)	He (10 MPa)
Working gas system	Compressor Check valves Storage tank(s) Power control system	Hermetically sealed
Cooling system	Water pump Radiator Blower fan	Water pump Radiator Blower fan
Auxiliaries	Starter motor[a]	Starter motor[a]
Control system	Microprocessor	Microprocessor

[a]For stand-alone applications.

be hermetically sealed therefore eliminating the need for a gas makeup system. Analysis can show that the same high brake efficiency as a percentage of Carnot efficiency is expected from either the free-piston or kinematic Stirling configurations.[3,4] The expected high efficiency, along with the inherently simpler design, make the free-piston Stirling the engine of choice for the long term solar application. It should be noted that when comparisons of data and information from similar type engines are made, which were designed for different duty cycles (i.e., automotive and solar), they can be misleading and may lead to wrong conclusions.

ADVANCED STIRLING CONVERSION SYSTEM

DOE signed a cooperative Interagency Agreement (IAA) in 1985 with NASA Lewis to provide technical management for the Advanced Stirling Conversion System (ASCS) Project. Under this IAA, the ASCS Project has provided DOE/SNLA with two conceptual designs of free-piston Stirling engine systems, which were completed in 1987. Both concepts have the potential of meeting DOE's system and engine performance projections (Figs. 3 and 4) while appearing to meet or exceed the DOE long term cost goals. The DOE cost goals are shown in Table II.[5]

The receiver and conversion costs have been combined to provide a total system cost for the ASCS, excluding the concentrator. The ASCS total cost goal is based on collecting concentrated solar energy into a receiver from an 11 m parabolic dish while providing 25 kW or more of electrical power to the utility grid. Both the MTI and STC ASCS concepts were evaluated independently by Pioneer as stand alone systems for the cost study, which we believe to be a more meaningful comparison. The manufacturing rate for the cost study is 10 000 units/year. Based on the Pioneer study, both systems (in 1984 dollars), the MTI ASCS at \$363/kWe, and the STC ASCS at \$308/kWe can easily meet the DOE long term goal of \$452/kWe.

Each ASCS consists of a solar energy receiver, a liquid metal heat transport system, a free-piston Stirling engine, the engine heat rejection system, an alternator or generator either directly or indirectly coupled the engine to the utility grid, and the appropriate controls and power conditioning. The proposed concepts and the preliminary conceptual designs are discussed in Refs. 6 and 7. The final conceptual design completed by MTI[8] features a heat pipe receiver integrated with a free-piston Stirling engine/linear alternator conversion system. The STC[9] final conceptual design features a reflux boiler receiver integrated with a Stirling engine/hydraulic conversion system.

Objectives of the conceptual design tasks for the ASCS Project are as follows:

(1) Define the ASCS configuration
(2) Predict ASCS performance over a range of solar inputs
(3) Estimate system and major component weight
(4) Define engine and electrical power conditioning and control requirements

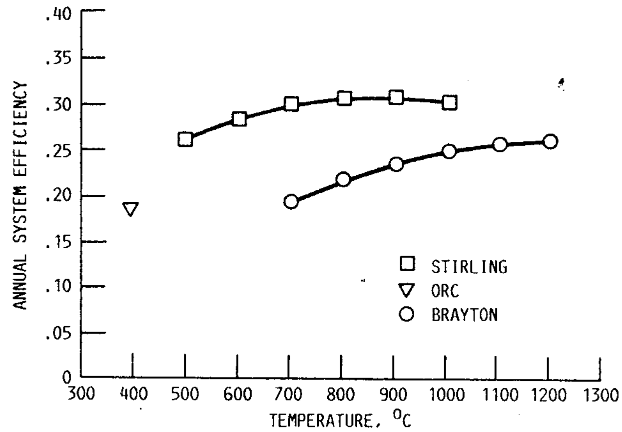

FIGURE 3. - SOLAR SYSTEM PERFORMANCE PROJECTIONS.

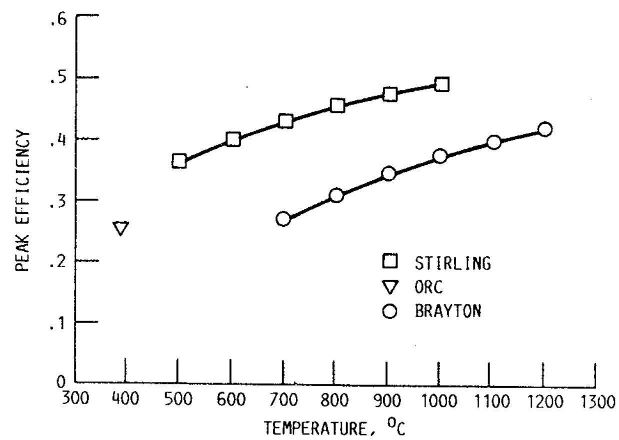

FIGURE 4. - PEAK ENGINE PERFORMANCE PROJECTIONS.

TABLE II. - DOE COST[a] GOALS

	Current technology	Long-term goals
Receiver, dollars/m^2	70	40
Conversion, dollars/kWe	380	300
ASCS total,[b] dollars/kWe	646	452
Energy cost, dollars/kWe	0.13	0.05

[a]1984 Dollars.
[b]Receiver (11-m concentrator) and conversion (nominal 25 kWe) combined.

(5) Define key technology needs not ready by the late 1980's in meeting goals
(6) Provide a manufacturability and cost evaluation for the engine power conversion system

The approach for designing the 25 kW solar conversion system for DOE/SNLA was to design with a clean sheet as recommended in earlier studies. The method used was to start from a system point of view which featured the free-piston Stirling engine along with the appropriate subsystems. This allowed for the proper optimization of the engine within the system to maximize both efficiency and power for the solar application. Proper evaluation of the various subsystem losses at an early stage of the design process, eliminate the need for compromise later on. The system is divided as shown below.

Receiver
Heat transport system
Conversion system:
  Stirling engine
  Power output device
Auxiliaries
Power conditioning and controls

The MTI and STC conceptual designs are considered unique yet complementary to each other. Each ASCS design features the Stirling engine, a liquid metal heat transport system as part of the solar receiver, a means to generate electric power, a cooling system, and the power conditioning and control system. Wherever possible, both conceptual designs include the use of existing technology which is expected to be available in the late 1980's. The MTI concept utilizes a heat pipe receiver integrated with the free-piston Stirling conversion system to directly convert the solar energy to electricity. The STC concept uses a reflux boiler receiver integrated with a Stirling hydraulic conversion system generating electricity indirectly using the hydraulic output to a hydraulic pump/motor coupled to a rotating alternator. The ASCS is being designed to mount on, and to receive concentrated solar energy from an 11 m test bed concentrator (TBC) located at the SNLA test facilities in Albuquerque, NM. The ASCS Project design requirements and the SNLA TBC characteristics are given in Ref. 7.

During the conceptual design process the specification for the operating temperature for the ASCS measured at the hot end (Stirling heater

TABLE III. - COMPARISON OF THE ASCS CONCEPTUAL DESIGNS

	MTI	STC
Heat supplied (peak), kWt	86.8	86.8
Electric power (peak), kWe	27.5	29.6
Heat supplied (nominal), kWt	75	75
Electric power (nominal), kWe	23.2	25.2
Efficiency engine (Q_{in} to PWR_{out}), percent	38.5	37.3
Efficiency (solar to electric), percent	30.9	33.6
Annual energy, kWh	59 200	65 200
Annual efficiency, percent	28.8	31.8
Receiver	Heat pipe	Reflux boiler
Receiver efficiency (vertical), percent	91.8	90.4
Liquid metal	Sodium (Na)	Potassium (K)
Heater head temperature, °C (K)	700 (973)	700 (973)
Cooler temperature, °C (K)	60 (333)	50 (323)
Engine frequency, Hz	60	46
Pressure, MPa (psi)	10.5 (1540)	17.9 (2630)
Temperature ratio, T_h/T_c	2.9	3.0
Working fluid	He	He with Freon buffer
Power conversion	Linear alt	Hydraulic pump with Ind. Gen.
Electric efficiency, percent	94.0	96.0
Electrical output	240 V, one phase	240 V, three phase
Power conditioning	Auto-transformer	None
Controls	Automatic	Automatic
Weight on TBC, kg (lb)	680 (1500)	869 (1914)
ASCS total cost, 1984 dollars	8429	7670
ASCS, dollars/kWe, 1984 dollars	363	304

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head) was decreased from 800 to 700 °C. This temperature reduction will increase material life by increasing the creep rupture and fatigue life and should minimize, where practical, potential liquid-metal problems such as corrosion. The predicted ASCS performance (solar to electric) at operating temperatures of 700 °C is about 31 percent for the MTI ASCS while the STC ASCS is about 33 percent. The estimated annual energy for both concepts is about 60 000 kWh. The specification for the nominal insolation of 950 W/m^2 provides about 75 kW of thermal energy to the receiver absorber surface. However, both concepts have been designed to operate continuously when the peak insolation of 1100 W/m^2 is available. This results in about 87 kW of thermal energy at the receiver. Designing for the peak insolation allows for an increase in annual energy production. A comparison of the MTI and STC concepts is provided in Table III. The MTI and STC conceptual designs are discussed in detail in Refs. 8 and 9, respectively.

MTI ASCS CONCEPTUAL DESIGN

MTI, the prime contractor, was responsible for project management, the design of the free-piston linear alternator conversion concept and system integration. MTI was teamed with Thermacore, Inc., Lancaster, PA, for the heat transport system and with Sanders Associates, Nashua, NH, for the solar receiver design. Pioneer Engineering and Manufacturing Co., Warren, MI, provided the independent manufacturing and cost analysis for the MTI design. At the design review held in June 1987 MTI recommended an ASCS configuration, shown in Fig. 5, which includes a heat pipe receiver integrated with a single piston Stirling conversion system with a passive (with no active feedback) vibration absorber for the baseline design. The ASCS is controlled with an autotransformer with a tuning capacitor in the load circuit to the utility grid. The estimated annual energy for the MTI ASCS is shown in Fig. 6. MTI divided the ASCS into the following subsystems:

(1) Receiver/heat transport system
(2) Engine/linear alternator
(3) Vibration absorber
(4) Engine mounts
(5) Cooling system
(6) Power control system

All the subsystems, except the power control system, can be mounted directly on the focal point of the 11 m concentrator. Each of the major systems are discussed below.

Receiver/Heat Transport System

The receiver/heat transport system is a single heat pipe on a hemispherical shell shown in Fig. 7. The solar energy is collected from an 11 m parabolic dish which focuses the solar energy through an 203 mm (8 in.) diameter aperture in the receiver face. The receiver has been designed to operate continuously with a nominal insolation of 950 W/m^2 providing about 75 kW of thermal energy to the absorber surface. The surface of the evaporator is covered with a powdered metal wick with a primary and a redundant circumferential/radial artery system. Sodium was chosen as the liquid metal for the heat pipe because the superior surface tension properties allow for easier wicking. The heat pipe cavity behind the absorber/evaporator surface is designed so that the condensed liquid drains by gravity to the arteries at the base of the evaporator shell. The use of the heat pipe for the heat transport system should minimize local hot spots and provide more uniform heating to ensure longer life for the Stirling heater head tubes.

Engine/Linear Alternator System

The single cylinder Stirling engine is integrated with a linear alternator to directly convert the energy to electricity to the grid. Figure 8 shows a cross section of the engine/alternator conversion system. This configuration uses only two moving parts, a displacer and a power piston. The heater head is designed to operate at a temperature of 700 °C (973 K). The working fluid is Helium at a mean pressure of 10.5 MPa (1520 psi). An annular configuration is proposed for the regenerator and cooler. Hydrodynamic gas bearings have been chosen for the conceptual design which allows the use of close tolerance, noncontacting seals which eliminate wear mechanisms during operation. A spin motor is conceptually shown to drive the power piston and displacer to create the hydrodynamic effect. The engine and the linear alternator are contained in a common vessel which allows for the conversion system to be hermetically sealed. A permanent magnet concept was selected for the linear alternator, using Neodymium-Boron-Iron magnets. The linear alternator is connected to a series tuning capacitor and to the grid through an autotransformer. A cooling system is incorporated for the stator to assure the proper temperature of the magnetic materials. The single phase linear alternator has been designed to provide 23.2 kWe (nominal) and 27.5 kWe (peak) to the utility grid.

Vibration Absorber

A passive (with no active feedback) vibration absorber was chosen for the single piston Stirling conversion system configuration. The mass and spring stiffness was selected so that the resonant frequency of the vibration absorber is the same as the nominal operating frequency of the engine, 60±0.6 Hz.

Cooling System

The heat rejection system is a closed system which is divided into two parallel loops: (1) for the engine cooler, and (2) for the alternator stator. MTI recommended automotive type cooling system components which include a radiator, a blower fan, and a coolant pump.

Power Control System

The linear alternator is connected to the utility grid through an autotransformer and a series tuning capacitor. The frequency and the

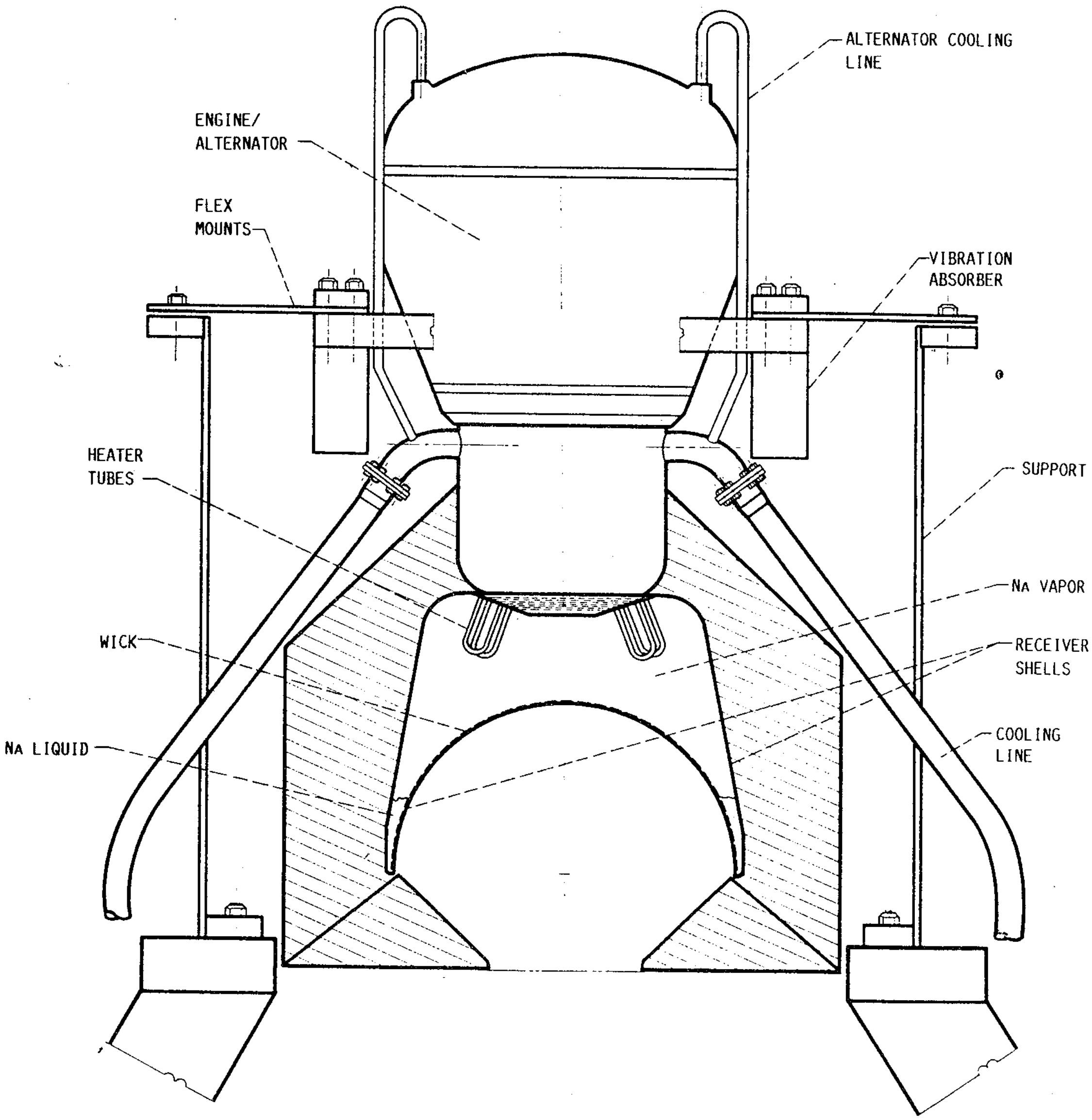


FIGURE 5. - MTI'S SINGLE PISTON STIRLING ENGINE ASCS CONFIGURATION.

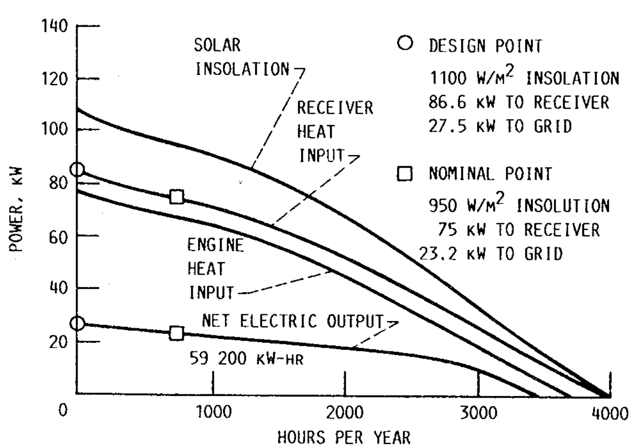
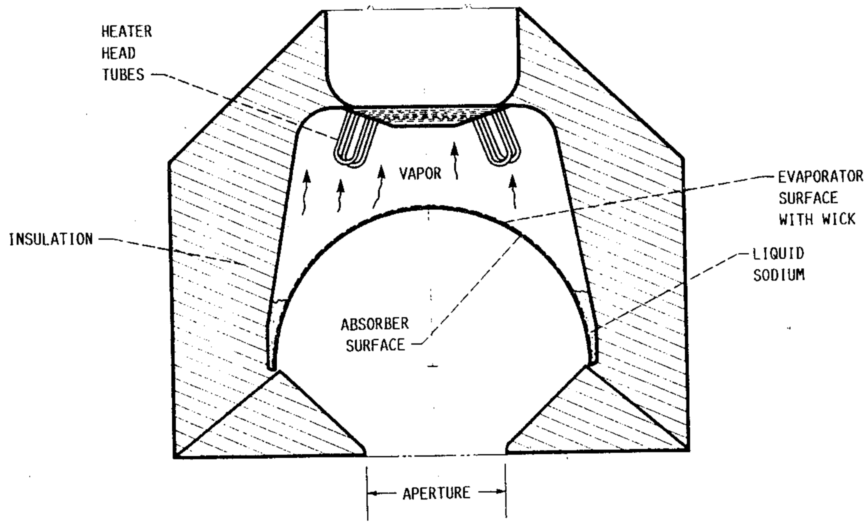
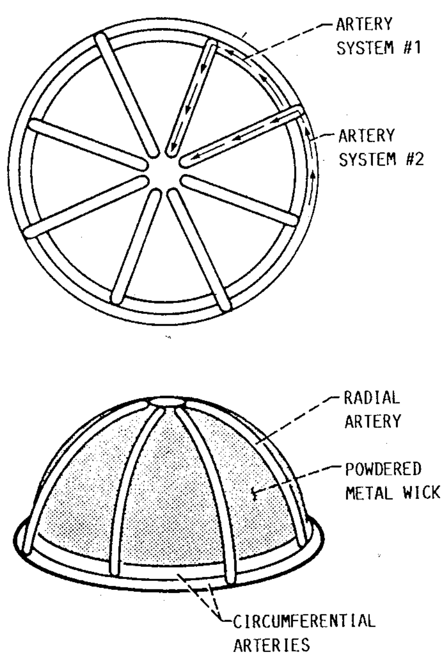


FIGURE 6. - MTI'S ANNUAL ENERGY PROJECTION.



(A) HEAT PIPE RECEIVER.

FIGURE 7. - HEAT TRANSPORT SYSTEM.



(B) HEAT PIPE EVAPORATOR.

FIGURE 7. - CONCLUDED.

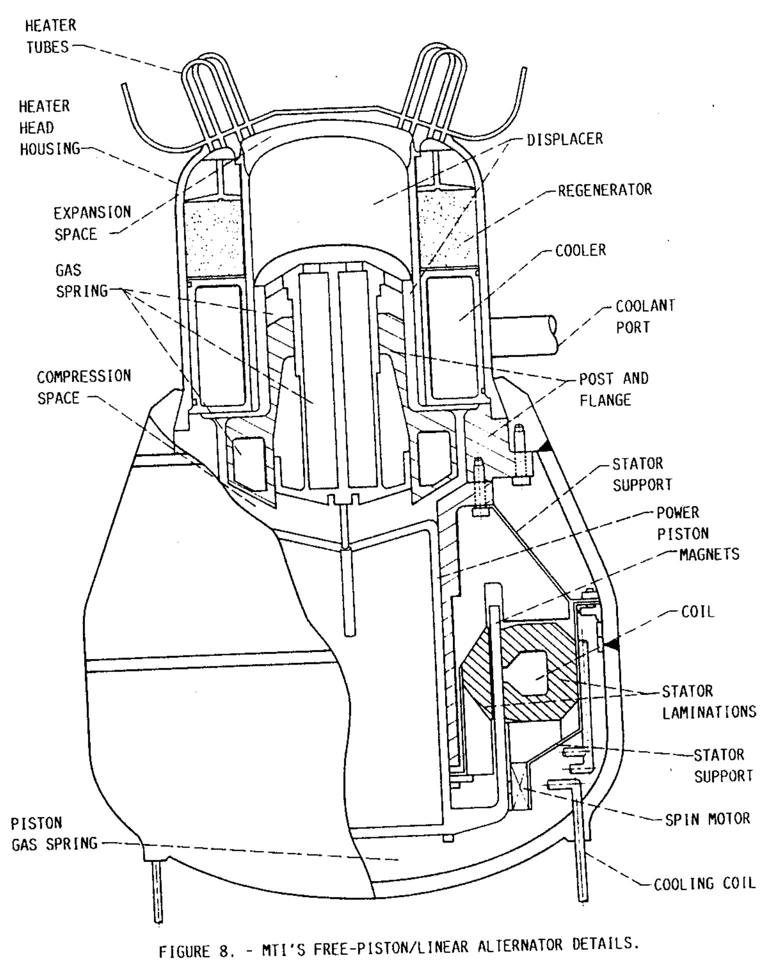


FIGURE 8. - MTI'S FREE-PISTON/LINEAR ALTERNATOR DETAILS.

autotransformer output voltage are essentially constant and established by the grid. The voltage at the alternator terminals is adjusted to match the changes in power while keeping the heater head temperature at its design point. The series capacitors used to compensate for the internal inductance of the linear alternator assure stable operation of the Stirling conversion system.

Controls

Fully automatic, unattended operation is planned for the ASCS.

STC ASCS CONCEPTUAL DESIGN

STC, the prime contractor, was responsible for project management, the design of the free-piston Stirling/hydraulic conversion concept and system integration. STC was teamed with Thermacore, Inc., Lancaster, PA, for the heat transport system and with Sanders Associates, Nashua, NH, for the solar receiver design. Pioneer Engineering and Manufacturing Co., Warren, MI, provided the independent manufacturing and cost analysis for the STC design. Consultants used during the conceptual design process were: Gedeon Associates, Athens, OH, for the thermodynamic simulation; Saaski Technologies, Inc., Seattle, WA, as a the heat transport consultant; and Westinghouse Hanford Co., Hanford, WA, for the high temperature materials expertise. At the design review held in July 1987, STC recommended an ASCS configuration, shown in Fig. 9, which includes a reflux boiler receiver integrated with the Stirling/hydraulic conversion system. A commercial hydraulic pump/motor and an induction generator were identified to convert the hydraulic output to electricity for the grid. The estimated annual energy for the STC ASCS is shown in Fig. 10. The ASCS is divided into the following subsystems:

(1) Receiver/heat transport system
(2) Engine/hydraulic output
(3) Hydraulic pump/induction generator
(4) Cooling system
(5) Power control system
(6) Controls

The STC study included both a stand alone ASCS and an array of up to 20 ASCS's. The Pioneer evaluation concluded that the array configuration was actually more expensive and would increase the capital cost about 10 percent; therefore, only the stand alone ASCS will be discussed. All of the subsystems can be mounted directly on the focal point of the 11 m concentrator. Each of the major systems are discussed below.

Receiver/Heat Transport System

For the receiver/heat transport system a reflux boiler (Fig. 11) was chosen over a number of candidates. The energy is collected from an 11 m solar concentrator which focuses the energy through an 203 mm (8 in.) diameter aperture in the receiver face. The receiver has been designed to operate continuously with a nominal insolation of about 950 W/m^2 providing about 75 kW of thermal energy to the absorber surface. Potassium was chosen as the liquid metal for the reflux boiler because the higher vapor pressure at 700 °C allows for easier boiling. The potassium is evaporated, similar to the operation of a double boiler, to provide vapor which results in a uniform temperature at the Stirling heater head tubes. The system is configured so that the heater head tubes are never submerged in the potassium pool, regardless of the concentrator elevation angle. A disadvantage of this boiler configuration is the large amount of liquid potassium inventory. The use of the reflux boiler for the heat transport system should provide a simple and uniform method for heating the heater head tubes and also minimize any local hot spots ensuring long life.

Engine/Hydraulic Output

The free-piston Stirling/hydraulic engine (STIRLIC) is hermetically sealed with the use of metal bellows. The engine delivers high pressure hydraulic fluid to a commercial hydraulic pump/motor which is connected to a commercial induction generator to convert the energy to the utility grid. Figure 12 shows a cross section of the engine/hydraulic conversion system. The heater head is designed to operate at a temperature of 700 °C (973 K). The working fluid is Helium at a mean pressure of 17.9 MPa (2630 psi). An annular configuration is proposed for the regenerator and cooler. The displacer employs metal bellows seals which allow the working fluid to be hermetically sealed and is connected hydraulically to a stabilizer mechanism. The engine working gas is sealed from the hydraulic fluid by use of the metal bellows, which are pressure balanced to provide very long life. The power pistons are arranged in an opposed piston configuration and also employ metal bellows seals. The power pistons, the displacer rod and the stabilizer/controller are immersed in hydraulic fluid which provides full film hydrodynamic lubrication of all sliding parts. Conceptually the STIRLIC utilizes a completely automatic internal lubrication and makeup system.

Hydraulic Pump/Induction Generator

The hydraulic motor selected is a commercial variable displacement motor coupled to a commercial rotary induction generator. Control is achieved through the automatic variation of the hydraulic motor displacement. The three phase induction generator has been sized to provide 25.2 kWe (nominal) and 29.6 kWe (peak) to the utility grid.

Cooling System

The engine cooling system requires industrial grade components which include a radiator, cooling fan and cooling pump.

Power Control System

Automatic regulation of the inlet pressure for the hydraulic pump is a factory option. No control is required for the induction generator or the power output circuit when operating on a grid. Frequency and voltage are established by the grid. Under a majority of loading conditions, the power

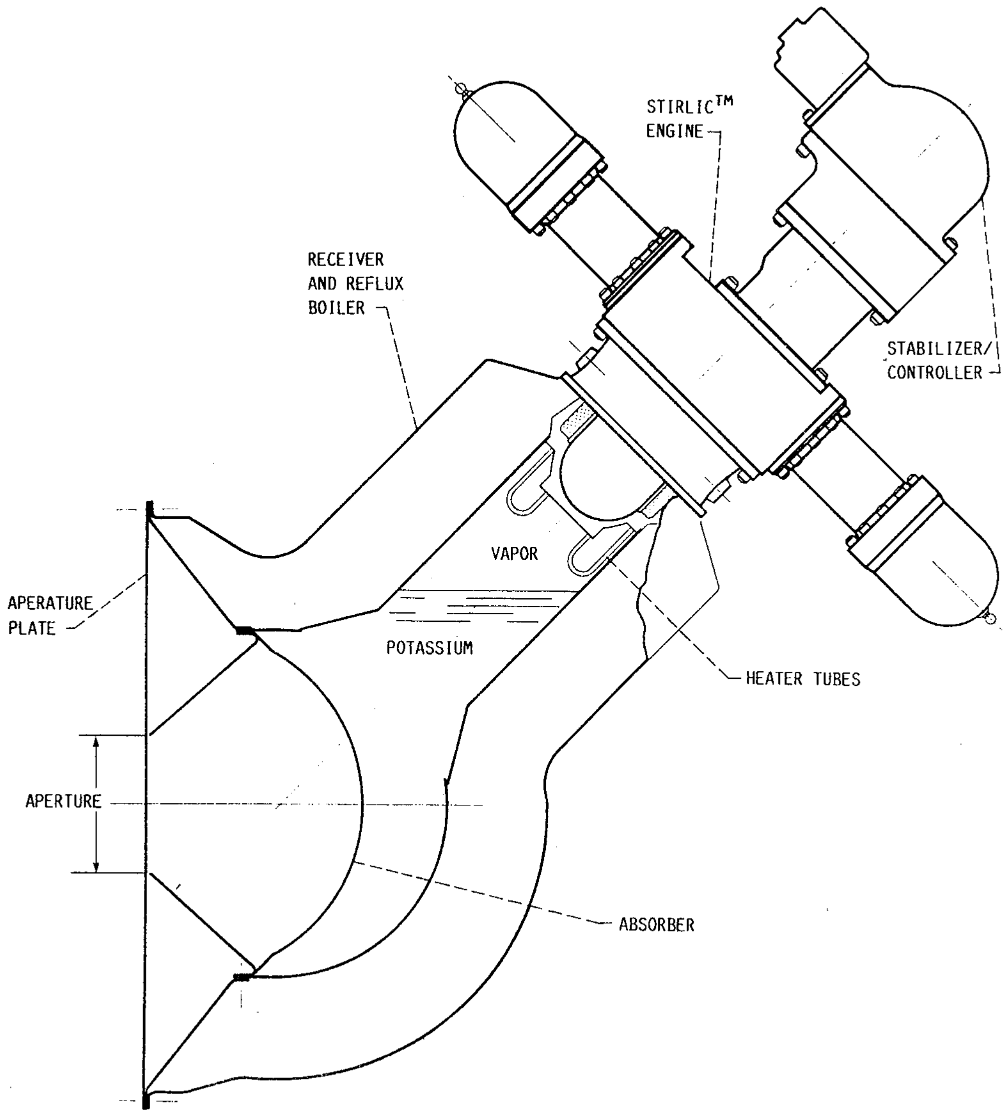


FIGURE 9. - STC'S STIRLING/HYDRAULIC ASCS CONFIGURATION.

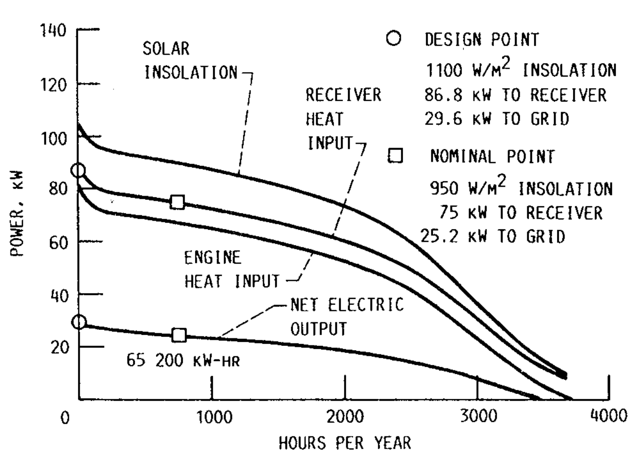


FIGURE 10. - STC'S ANNUAL ENERGY PROJECTION.

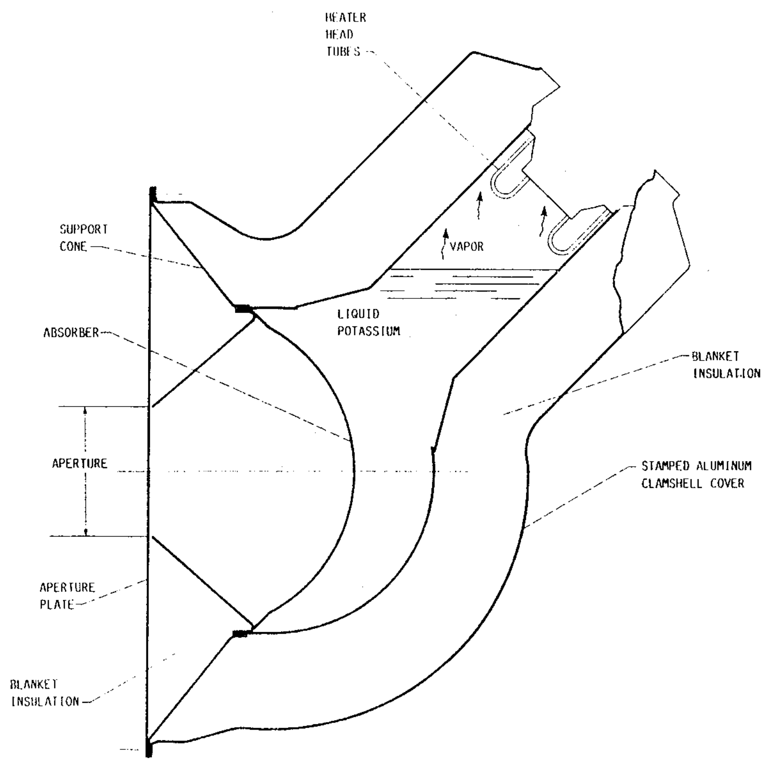


FIGURE 11. - REFLEX BOILER HEAT TRANSPORT SYSTEM.

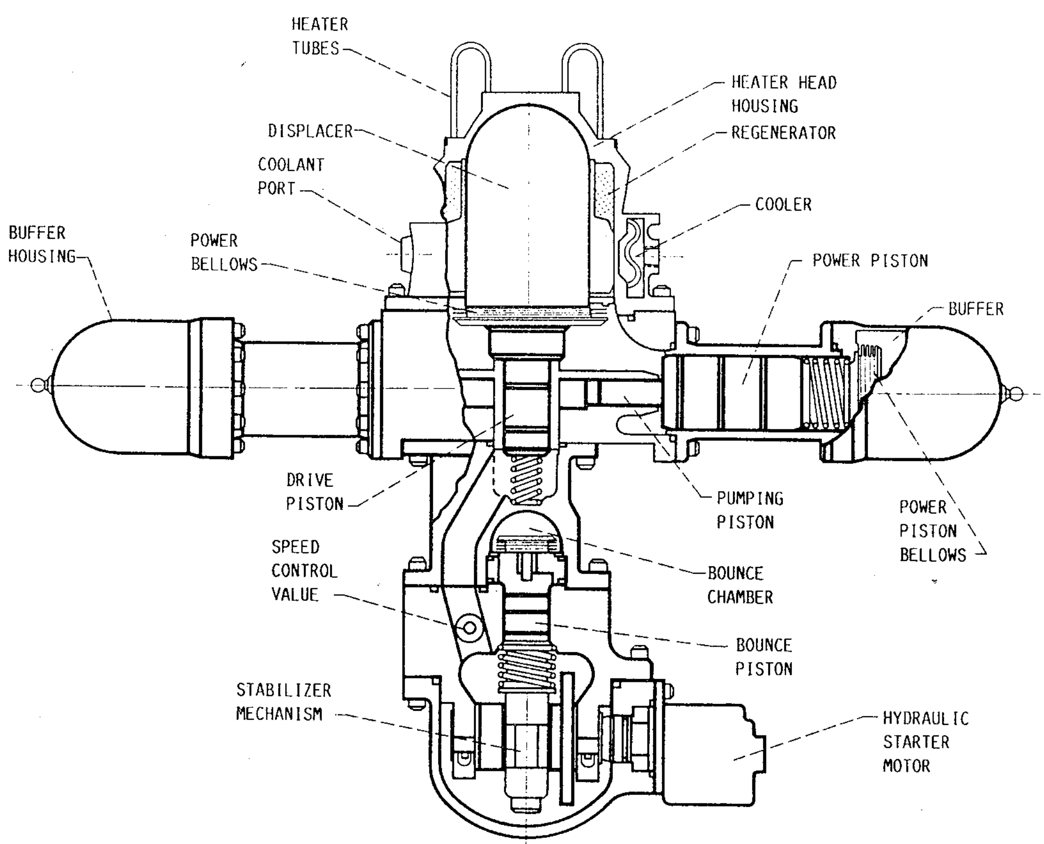


FIGURE 12. - STC'S FREE-PISTON/HYDRAULIC DETAILS.

factor is greater than 0.85; therefore, no power factor correction is required.

Controls

Fully automatic, unattended operation is planned for the ASCS.

MANUFACTURING AND COST ANALYSIS

Pioneer Engineering and Manufacturing Company, Warren, MI, provided an independent manufacturing evaluation and cost analysis for both the MTI and STC conceptual designs. Pioneer maintained dialogues with both contractors throughout the conceptual design process to assure the proposed concepts were manufacturable. The methodology for the evaluation of the conceptual designs utilized Pareto's Law to forecast both system and subsystem cost. The manufacturing rate used for this study was 10 000 ASCS units/year. Pareto's Law states that 20 percent of the major components constitute 80 percent of the total cost. This methodology was believed to be an accurate predictor for the comparison of both conversion concepts, the free-piston Stirling linear alternator and the free-piston Stirling/hydraulic. The ASCS was divided by functional groups or subsystems for the detailed comparison. Components selected for detailed costing are believed to be functionally representative for both the system and each subsystem. The production volume was given as 10 000 units/year. Total costs reflect the use of Michigan labor and material costs for 1986 and were extrapolated to reflect the DOE goals in 1984 dollars. Material costs are a major portion of the ASCS projected costs. The ASCS projected costs are shown in Table IV. Detailed information is provided in Refs. 8 and 9.

TABLE IV. - ASCS PROJECTED COSTS[a]

	MTI	STC
Receiver/heat transport system, dollars	727[b]	155[c]
Stirling engine, dollars	4843	3269
Power generation, dollars	1304	3323[d]
Power conditioning, dollars	542	-----
Cooling system, dollars	1014[d]	1014[d]
Total ASCS, dollars	8430	7761
ASCS, dollars/kWe	363[e]	308[f]

[a]In 1984 dollars.
[b]Heat pipe.
[c]Reflux boiler.
[d]Commercial equipment.
[e]Nominal rating 23.2 kWe.
[f]Nominal rating 25.2 kWe.

The independent assessment by Pioneer was completed in December 1987. The results indicate that both free-piston Stirling concepts are manufacturable and can easily meet the DOE long term cost goals of less than $450/kWe.

CONCLUDING REMARKS

Both conceptual designs meet all of the ASCS Project objectives. The Stirling engine has been identified by DOE as one of the most promising heat engines for terrestrial applications. Free-piston technology currently being developed at NASA Lewis for space and terrestrial applications has the potential to easily meet DOE's goals for performance and cost. Common requirements for the terrestrial and space applications include high efficiency, and very long life with high reliability. Both the MTI and STC conceptual designs which feature the free-piston Stirling in an Advanced Stirling Conversion System are unique and complementary to each other. The MTI concept incorporates a heat pipe receiver integrated with a Stirling/linear alternator conversion system to convert electricity directly to the grid. The STC concept incorporates a reflux boiler receiver integrated with a Stirling/hydraulic conversion system to a hydraulic pump/motor coupled to a rotating induction generator to provide electricity to the grid. An independent evaluation by Pioneer indicates that both concepts are manufacturable and can easily meet DOE's long term cost goals.

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Report Documentation Page

NASA
National Aeronautics and Space Administration

1. Report No. NASA TM-102085 DOE/NASA/33408-3	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Comparison of Conceptual Designs for 25 kWe Advanced Stirling Conversion Systems for Dish Electric Applications		5. Report Date 6. Performing Organization Code
7. Author(s) Richard K. Shaltens and Jeffrey G. Schreiber		8. Performing Organization Report No. E-4806 10. Work Unit No. 776-81-63
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		11. Contract or Grant No. 13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address U.S. Department of Energy Office of Solar Heat Technologies Washington, D.C. 20545		14. Sponsoring Agency Code

15. Supplementary Notes

Final Report. Prepared under Interagency Agreement DE-AT04-85AL33408. Prepared for the 24th Intersociety Energy Conversion Engineering Conference, cosponsored by IEEE, AIAA, ANS, ASME, SAE, ACS, and AIChE, Washington, D.C., August 6-11, 1989.

16. Abstract

The Advanced Stirling Conversion System (ASCS) Project is managed by NASA Lewis Research Center through a cooperative Interagency Agreement with DOE. Conceptual designs for the ASCS's were completed under parallel contracts in 1987 by Mechanical Technology Inc. (MTI) of Latham, NY, and Stirling Technology Company (STC) of Richland, WA. Each design features a free-piston Stirling engine, a liquid metal heat pipe receiver, and a means to provide about 25 kW of electric power to a utility grid while meeting DOE's long term performance and cost goals. An independent assessment showed that both designs are manufacturable and have the potential to easily meet DOE's long term cost goals.

17. Key Words (Suggested by Author(s)) Free-piston Stirling engine Advanced Stirling Conversion System Solar dish electric	18. Distribution Statement Unclassified – Unlimited Subject Category 85 DOE Category UC-96

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	14	A03

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161